Development of low-Cost Satellite Communications System for Helicopters and General Aviation[1]

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ABSTRACT

In this paper, the development of low-cost satellite communications (SATCOM) system for helicopters and General Aviation (GA) aircrafts is described. System design and standards analysis have been conducted to meet the low-cost, light-weight, small-size and low-power system requirements for helicopters and GA aircrafts environments. Other specific issues investigated include coding schemes, spatial diversity, and antenna arraying techniques. Coding schemes employing Channel State Information (CSI) and interleaving have been studied in order to mitigate severe banking angle fading and the periodic RF signal blockage due to the helicopter rotor blades. In addition, space diversity and antenna arraying techniques have been investigated to further reduce the fading effects and increase the link margin.

INTRODUCTION

Helicopters and General Aviation (GA) aircrafts, due to their existing limited coverage communications system, have a strong need for satellite communications (see Fig. 1). Jet Propulsion Laboratory (JPL) under a contract with the Federal Aviation, Administration (FAA), has been conducting studies for the development of low-cost, small-size, light-weight, real-time satellite communications (SATCOM) specifically for the unique operational environment and requirements of both helicopters and GA aircrafts. This system, under development, is planned to be demonstrated in the 1996 time frame.

This paper first discusses system design and standards issues for such a SATCOM system, identifies cost drivers, and recommends alternative cost effective options. The developments in the area of coding and modulation in reducing the effect of the rotor blade shadowing and improving the system performance are described next. These improvements are in addition to the solutions developed, published, and presented earlier [1,2]. Finally, in the area of antenna subsystem design, further antenna options identified will be explained, Table 1 summarizes terminal design options. Figures 2 and 3 depict basic terminal design by showing block diagrams for single antenna design and multiple antenna arraying techniques respectively, while applying developed coding schemes. In this paper, the general discussion has been applied to helicopters and the Inmarsat-3 satellite in setting the minimum requirements. This approach will cover cases for GA and other satellites (Iridium and AMSC) discussed earlier [1].

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SYSTEM DESIGN

This section identifies the key system cost drivers along with recommendations for alternative cost effective option(s) and how an adaptation of these specifications and standards can significantly reduce the overall cost of the terminal development. This study was performed after a comprehensive review of the existing specifications and standards that have been established by the various governing groups, in addition to conducting an industry survey.

To be practical and as realistic as possible, system options, and cost estimates presented here are as a result of extensive industry search of off-the-shelf commercially available satellite communication products. In key areas and in most cases, a formal industry Request For Information (RFI) has been executed. Furthermore, to support a low-cost proposed solution, thirty-six different scenarios for forward and return link budgets have been conducted and analyzed for the various cost effective options under consideration, These included link budget runs for O, 3, and 6 dBic antenna options for both data (A-BPSK [3] Differential, BER of 10E-5, from 600 to 2400 bps) and voice (A-QPSK [4] and [5] Coherent, BER of 10E-3, for 2400 and 4800 bps). Depending on the various options considered, the link margin varied.

Preliminary analysis indicate that O dBic (single or multiple) or 3 dBic gain antenna maybe a reasonable compromise between system cost and performance, A more realistic industry standard can certainly help reduce the overall cost of the system. It is also worth noting that in these link budget analyses extreme attention was paid to the satellite power being used. This is an important factor since the amount of satellite power used will affect the final operational cost and the attractiveness of the service to the end users. A low-cost terminal by itself will not have any value unless the operational cost is reasonable, and competitive with other existing communications systems as WC]].

Inmarsat-3 Satellite System: Higher EIRP, Cheaper Terminals

The Inmarsat-3 satellite system not only has the global beam coverage of the former generation satellite systems, but also provides regional spot beam coverage with a higher EIRP (8.4 dB more, the EIRP for Inmarsat-3 total regional spot beam is 47.4 dBW whereas Inmarsat-2 has a total global beam EIRP of 39.0 dBW). This results in the availability of extra power to close the link. By placing the extra available power on-board the satellite (making the satellite more expensive), less powerful (less costly) ground equipment will be necessary.

New Voice Codec: 4800 bps, Low Bit Rate, Yet Good Voice Quality

Significant advances have been made in speech compression algorithms since the initial terminal designs were completed, Near-toll quality voice algorithms now are commercially available at 4800 bps. Switching to the low bit rate, rather than the current 9600 bps, would translate into less power requirements and therefore reduced system cost. In some applications, the possibility of 2400 bps exists, resulting in further system power savings.

Antenna Subsystem: O, 3, 6 dBic options, Higher Gain, More Complex but Still Low-Cost

The high-gain (12 dBic) mechanically-steered antenna design is too expensive to meet the cost requirements of helicopters and GA market. Therefore, as was identified earlier

[1,2], the possibility of using low-gain (O dBic) low-cost ($150)[2] antenna exists. However, in order to increase the link margin further and also place less power requirements on the terminal, therefore making it less costly, potential use of medium-gain (3 or 6 dBic) low-cost ($300-$500)[2] omnidirectional antennas have been investigated. The coverage of these antennas will be over a volume from zenith to approximately 15 degrees above the horizon - i.e. comparable to the coverage of the Inmarsat System Definition Manual (SDM) low-gain antenna specification, As discussed in more detail in the antenna section, the novel design of the 3 and 6 dBic antennas will be more complex than the O dBic antenna option.

Coding: Applying Channel State Information (CSI), Reduced Shadowing Effect by 0.8 dB

To provide more power to the terminal, reduce the system cost, and at the same time, minimize the effect of rotor blade shadowing, Channel State information (CSI) techniques have been applied. In this scheme, through signal processing techniques, the shadowing effect can be almost immediately detected and compensated for. In the case of the one antenna system on the helicopter (Fig. 2), simulations indicate that employing CSI results in an additional gain of 0.8 dB. This subject is discussed further and in more detail in the coding section of this paper.

Antenna Subsystem: Employing Multiple Antennas (Space Diversity)

Using multiple low-cost antennas (Fig. 3) can also result in increased system power and potential reductions in the overall cost of the system [2]. Specifically, the potential of using two or three antennas on the helicopter (space diversity) in the receive mode and applying CSI has been investigated (Table 1). Simulations indicate that with a two antenna scheme and applying CSI, there will be nearly a gain of 3 dB (when neither of the antennas arc blocked) or no gain improvement but the shadowing effect removed completely (when one of the antennas is blocked). This subject is further discussed in the coding section of this report,

High Power Amplifier (HPA): Less Power, Less Complex, Less Costly

The current specification on the High Power Amplifier (HPA) is for up to 80 watts of RF output power. In our system design this value should be able to be scaled back to a maximum of 20 watts. This reduction in power means that the new HPA would probably be small enough to be co-located with the antenna and the LNA/Diplexer. This will also minimize the cabling losses and costs. Using a low power HPA can also eliminate the complex RF power adjustment electronic design in the current systems which optimizes the number of users that can be simultaneously transmitted on a single aeronautical terminal. Currentl y, systems allow for incremental 1 dB changes in the transmit power over a range of 15 dB. The new proposed design, at worse, should be able to operate with a two state transmit power schemes at 3 dB difference between the two states. At the same time, the reduction of the necessary RF output power to 20 watts (from 80 watts) also significantly reduces the demands and the accompanying costs of the Diplexer as well. The cost of the HPA is estimated, through formal industry RFI search, to be around $2,000.

[2] Quoted price is for large quantities and does not include FAA certification cost.

CODING

In earlier studies [1], various coding and differential modulation techniques were proposed and investigated to mitigate the shadowing effect of the helicopter rotor blades. This area has been further explored by developing and applying other various coding and coherent modulation schemes in further reducing the effect of the rotor blade blockage and improving the system performance (Table 1). These improvements arc in addition to the solutions developed earlier [1].

Two types of demodulation have been considered, namely coherent and non-coherent demodulation. Time diversity to combat shadowing was accomplished by using coding and interleaving. Space diversity was also considered by employing two antennas. The system consists of a convolutional code (constraint length 7, rate 1/2) with soft decision Viterbi decoding and interleaving. Channel State Information (CSI) has now also been applied. CSI employs a power estimator over a window of time and compares it to a threshold in order to detect the presence of the shadowed signal. The estimate for the symbol at time k is obtained through:

$$\frac{1}{N}\sum_{i=-\frac{N-1}{2}}^{\frac{N-1}{2}}\left|r_{k+i}\right|^2 > \gamma,$$

where r_k is the received complex sample output of an integrate and dump circuit at time k, and γ is the threshold. N, the number of symbols in the estimator time window, is assumed to be an odd number. The number of symbols required for reliable estimation were determined by analysis and confirmed by simulation. Since the estimator works with a time window of several symbols, the edges of start and end of shadowed symbols cannot bc detected accurately. For the rate of 4800 bps, the shadow duration is about 38 symbols, and the estimator edge detection accuracy is about 3 symbols, so negligible performance degradation is expected relative to the perfect CSI case.
Simulation results arc summarized below.

Coherent, coded and interleaved A-QPSK modulation with CSI

One antenna subsystem with CSI (Fig. 4) - Simulation results indicate that at 4800 bps the loss due to 10% shadowing effect of the helicopter rotor blades i's 2.5 dB. However, using Channel State Information (CSI) helps to improve the performance of the Viterbi decoder by an additional 0.8 dB by measuring and monitoring degradation in the instantaneous received power. This includes the slight degradation expected, around 0.7 dB, from the optimum CSI case since the estimation of presence of a shadowing sample is not perfect. Therefore, in short, the net loss in the case of coherent demodulation 10% shadowing can bc reduced to 1,7 dB by applying CSI. This value compares to a loss of 1 dB in the case of non-coherent demodulation (without CSI) found earlier [1].

Two antenna subsystem with CSI (Fig. 5) - The option of having two separated antennas, where the distance between them is larger than the blade's shadow, have also been investigated. In this case the antennas arc shadowed in different times so that they can be selected or combined in order to enhance the system performance. The antennas are assumed to have equal coverage.

Without CSI estimate, the combining is just like adding the signals. In this case, results indicate a gain of 3 dB when both signals arc present, and loss of 3 dB when onc of the signals is absent duc to the shadowing. Gains or 1OSSCS indicated arc with respect to a single antenna subsystem.

With CSI available, the systcm performance can bc improved by using the weighted sum of the signal. Here the noise contribution of the shadowed antenna can bc eliminated almost complctely, leading to improved results. In this case, results indicate a gain of 3 dB when both signals arc present, or at worst no loss (relative to single antenna subsystem) when onc of the signals is absent duc to the helicopter rotor blades shadowing effect.

For the implementation of the two antenna subsystem, the RF signals can bc combined by using a controlled phase shifter, or using two separate channels and combining them at baseband. The second option is more practical since the combining will bc done by digital signal processing, and the phase diffcrcncc bctwccn the channels will be much easier to estimate.

Non-cohcrcnt combining - In non-cohcrcnt combining, two channels arc used. For each channel, non-cohcrcnt demodulation is performed, e.g. A-BPSK [3] demodulation. The soft decision outputs of the demodulators arc then combined. In this option, no phase information is required, leading to a simpler implementation of the system.

ANTENNA DESIGN

As was identified earlier [1 ,2], the possibility of using low-gain (O dBic) low-cost helix antenna exists. However, in order to increase the link margin further and also place less power rcquircmcnts on the terminal, thcrcforc making it lcss costly, the potential usc of medium-gain (3 or 6 dBic) low-cost omnidirectional antennas has been investigated and discussed below. Also, to mitigate signal blockage and fading, space diversity has been considered (Table 1).

The non-uniform physical body structure and rotor blades of the helicopter crcatc signal blockages and complex interference patterns that make wide angular coverage difficult to achieve . While employing a single, low-gain (O dBic) helix antenna is the lowest cost and most reliable, blockage and diffraction effects from the helicopter rotor blades and body degrade the radiation performance. To obtain preliminary predictions of the degradation characteristics of an antenna located in a helicopter environment, the Numerical Electromagnetic Code - Basic Scattering Code (NEC-BSC) [6] has been applied to a simple helicopter model shown in Figure 6. Figure 7 depicts radiation pattern of an isolated antenna before it is placcd on the helicopter and Figure 8 shows degradation effects for various cuts after the antenna is placed on the boom of the helicopter. As it can bc seen from Figure 8, the antenna pattern is distorted and gain drops of as much as 10 to 20 dB arc observed. To overcome some of these difficulties, and at the same time to increase the gain and coverage, several antenna configuration options have been considered. First, to increase the gain, various techniques in developing a low-cost medium-gain (3 and 6 dBic) antenna have been investigated. Then, to ovcrcomc blockage and diffraction effects space diversity and arraying techniques have been considered.

A rncthod for increasing the gain is to rcducc the covcragc, as is the case for a helix antenna, By placing several of thcsc antennas together in onc location and switching among them, a wider region can bc covcrcd resulting in a single medium-gain antenna. Considering this, there are various relatively complex options to achieve 3 or 6 dBic antenna gain from zenith to 15 degrees above horizon. Proposed options using helical antennas include: (1) Stacked helix array that switches between upper and lower hemispherical coverage modes; (2) 4-element scanning helix array; (3) switchable quadrifilar helix using feed network to control the excitation of each arm (lower hemispherical coverage may be distorted due to the helicopter body). Preliminary results indicate that it is feasible to develop an omni-directional 3 dBic antenna gain for the required coverage whereas a 6 dBic antenna is difficult to achieve.

Space diversity can be achieved by placing multiple antennas of low or medium-gain in various locations on the helicopter. For example, one antenna can be placed on the cabin and one on the boom or tail, or one on each side of the boom. In the case of space diversity, if the angular coverage of the antennas overlap and if they are separated by a distance greater than a wavelength, the antennas must not be coherently connected, since destructive interference will occur at specific angular directions. Instead a switching mechanism, such as CSI coding technique discussed earlier, must be applied to select the antenna with the highest signal level. In this case, the highest achievable system gain is that of a single antenna, assuming that the antennas are strategically located so that at any given point in time at least one of the antennas are not blocked by the rotor blade.

In summary, preliminary trade-off studies conducted among the available antenna options, the link budget analyses, the performance, complexity, and cost of the system indicate that single or multiple O dBic ($150) or 3 dBic ($300-$500) gain antennas may be a reasonable compromise (Fig. 2 and 3). The coverage of these antennas will be over a volume from zenith to approximately 15 degrees above the horizon - i.e. comparable to the antenna coverage of the Inmarsat SDM low-gain antenna specification. Further investigations and simulations results indicate that the preferred locations to place these antennas are on the boom or tail of the helicopter, as was found earlier [1].

CONCLUSION

There is a growing demand for low-cost SATCOM system for the helicopters and General Aviation (GA) aircrafts industry. This demand can be met by developing a low-cost real-time satellite communications terminal that meets the unique operational'environment of both helicopters and GA which include cost, size, weight, and power limitations.

System studies conducted indicate that these requirements can be met and are achievable. Key system cost drivers have been identified along with recommendations for alternative cost effective option(s) and how an adaptation of these specifications and standards can indeed significantly reduce the overall cost of the terminal development. In addition, further developments in the area of coding and antenna arraying in handling severe signal fading and in mitigating the RF signal blockage due to the helicopter blades have been discussed. Finally, extensive link budget analyses have been performed and various system options evaluated to ensure the affordability of the terminal, as well as low-cost operational usage by the end users.

In short, JPL, by working closely with the industry (satellite providers, avionics and antenna manufacturers) has been able to confirm the feasibility of a low-cost SATCOM system designed specifically for helicopters and GA by conducting both technical and market assessment. JPL has also been interacting with potential customers, both commercial and non-commercial, domestic and international, who have not only voiced a strong need for such a system but have also expressed interest in joint collaborations and partnerships. The list includes, Industry, Universities, FAA, NASA, and DOD.

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Table 1. Summary of Terminal Design Options
(4800 bps, BER=10-3)

Terminal Design Option	E_b/N_o Required (dB)	Comments
Single Antenna, QPSK	5.0	Basic Coherent System
Single Antenna, DPSK	6,9	Basic Differential System
Two Antennas Combined, QPSK	1,4	Phase Estimation Increased Complexity
Two Antennas Combined, DPSK	4.6	Increased Cost and Complexity
Two Antennas Switching, QPSK	2.5	Filter Banks Increased Complexity
Two Antennas Switching, DPSK	5.8	Increase Cost
Two Antennas CSI, QPSK	4.2	Improved System Performance at a Reasonable Cost Increase
Three Antennas CSI, QPSK	4.2	Dual Receive Single Transmit

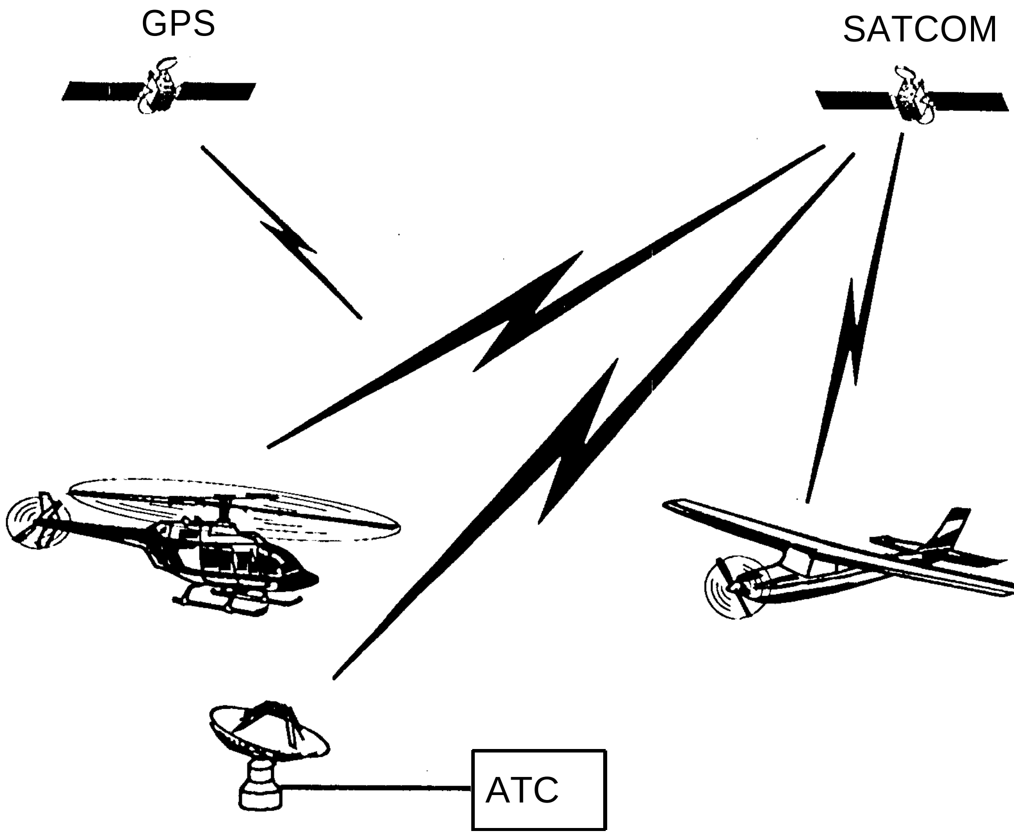


Figure 1. Helicopter and General Aviation Satellite Communications System

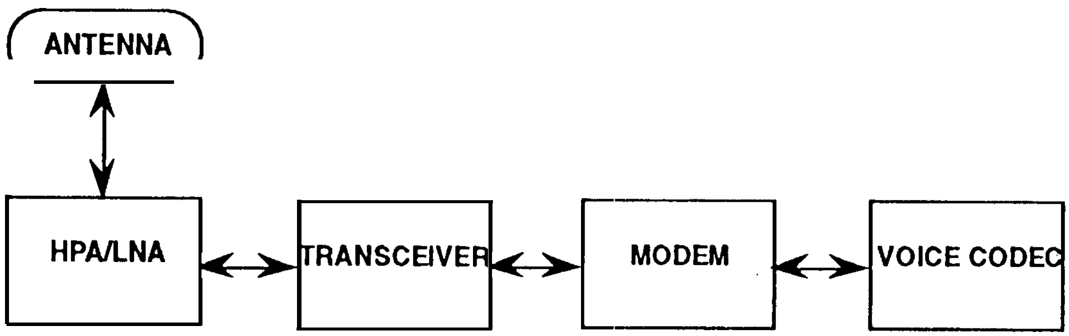


Figure 2. Block Diagram of Single Antenna Design Option

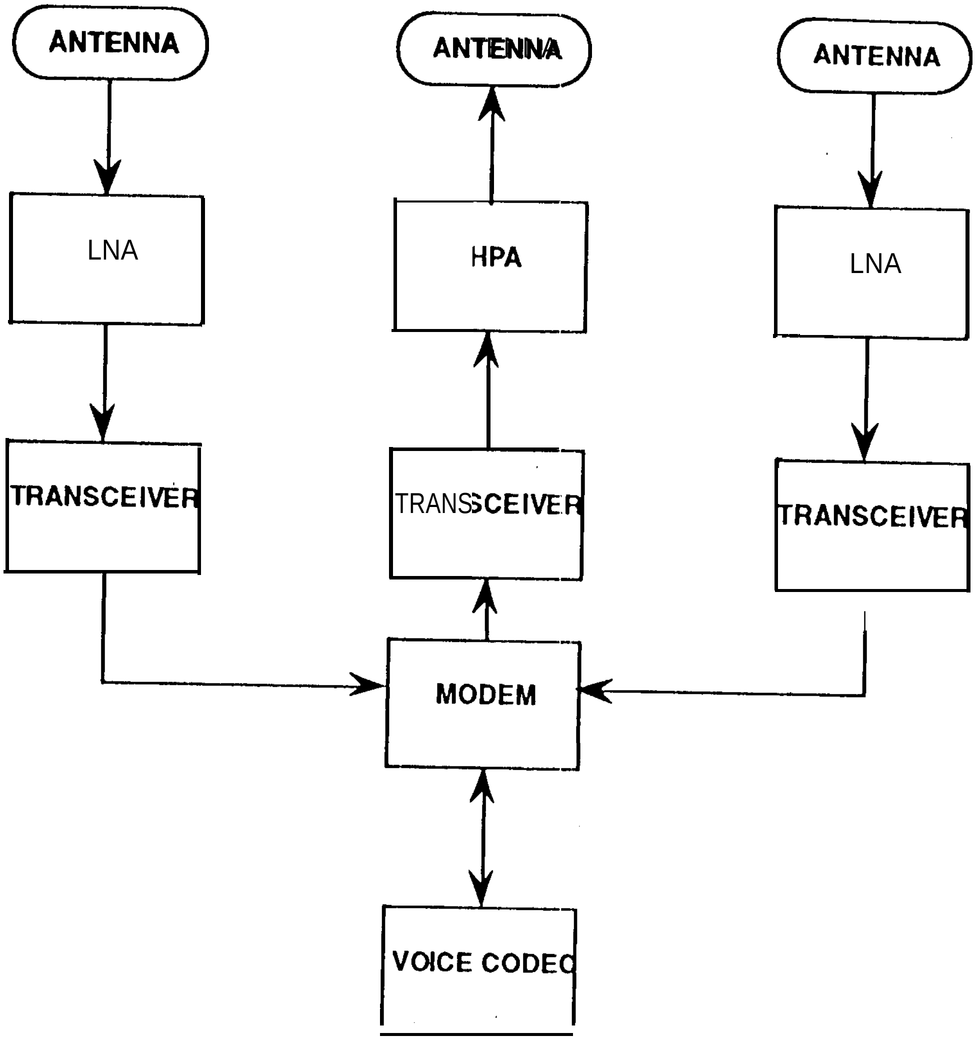


Figure 3. Block Diagram of Dual Receive Antenna CSI Modem, with Single Transmit Antenna Design Option

Fig. 4 **Performance of Coded QPSK**

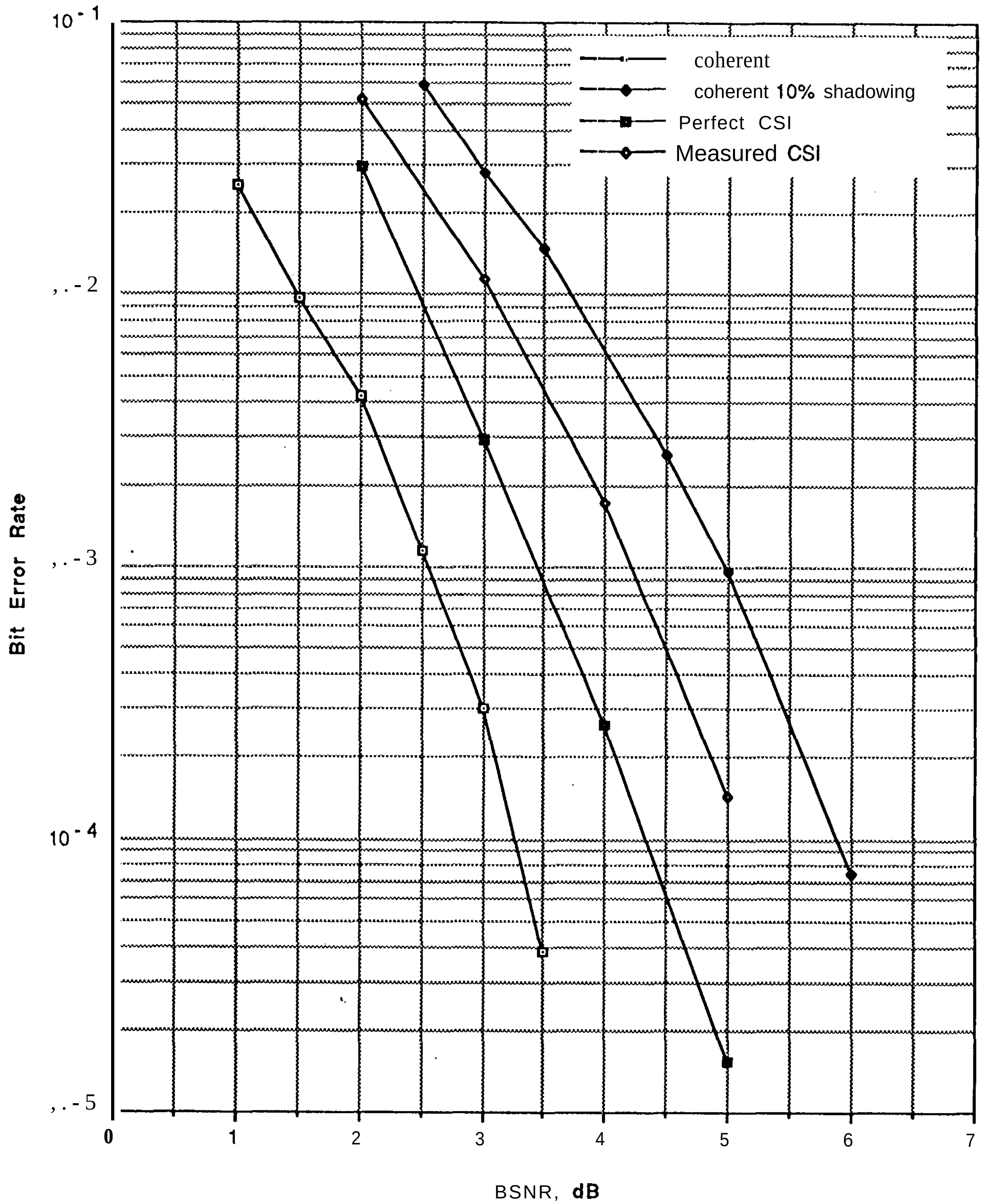
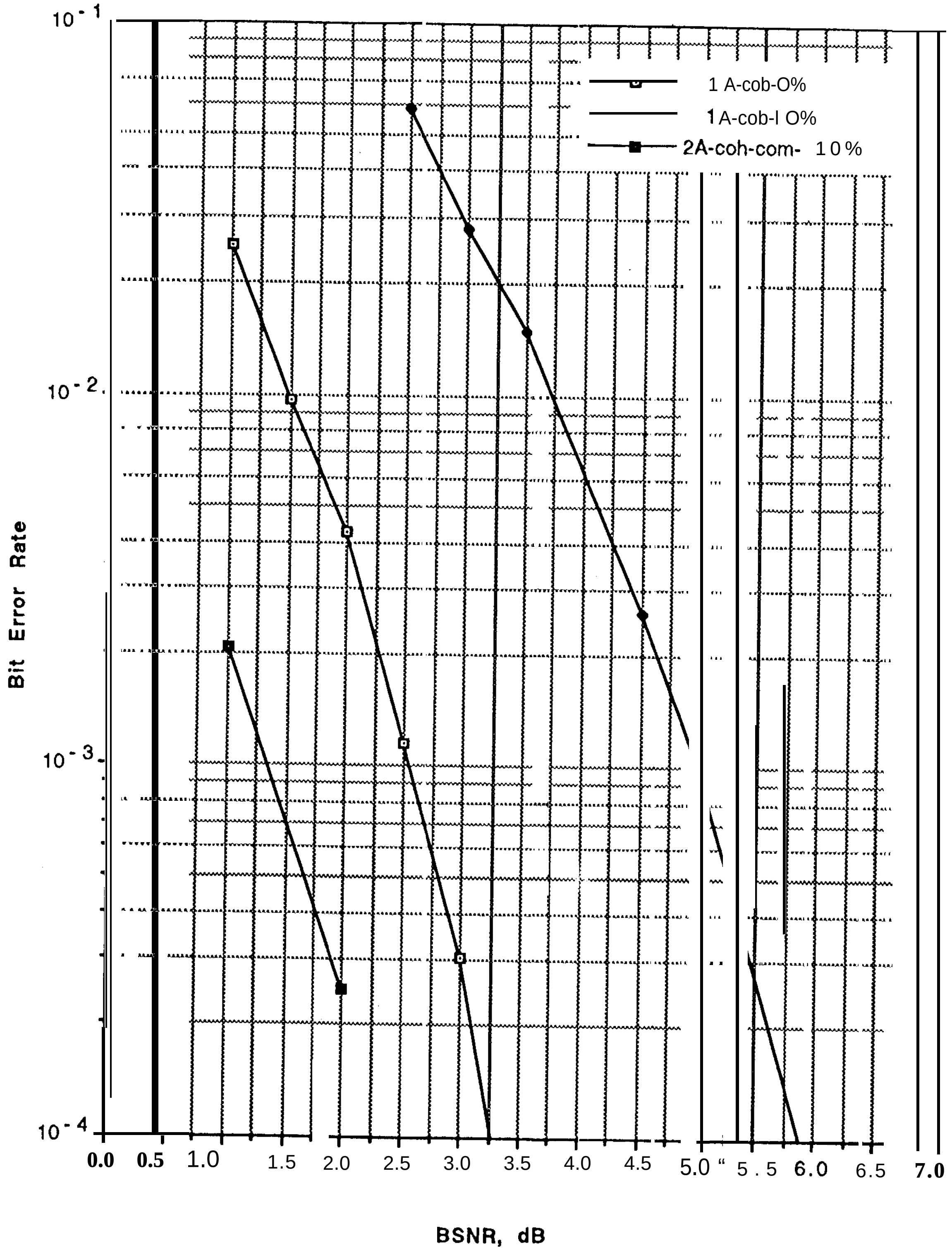


Fig. 5 **Performance of Coherent Coded System with two Antennas**



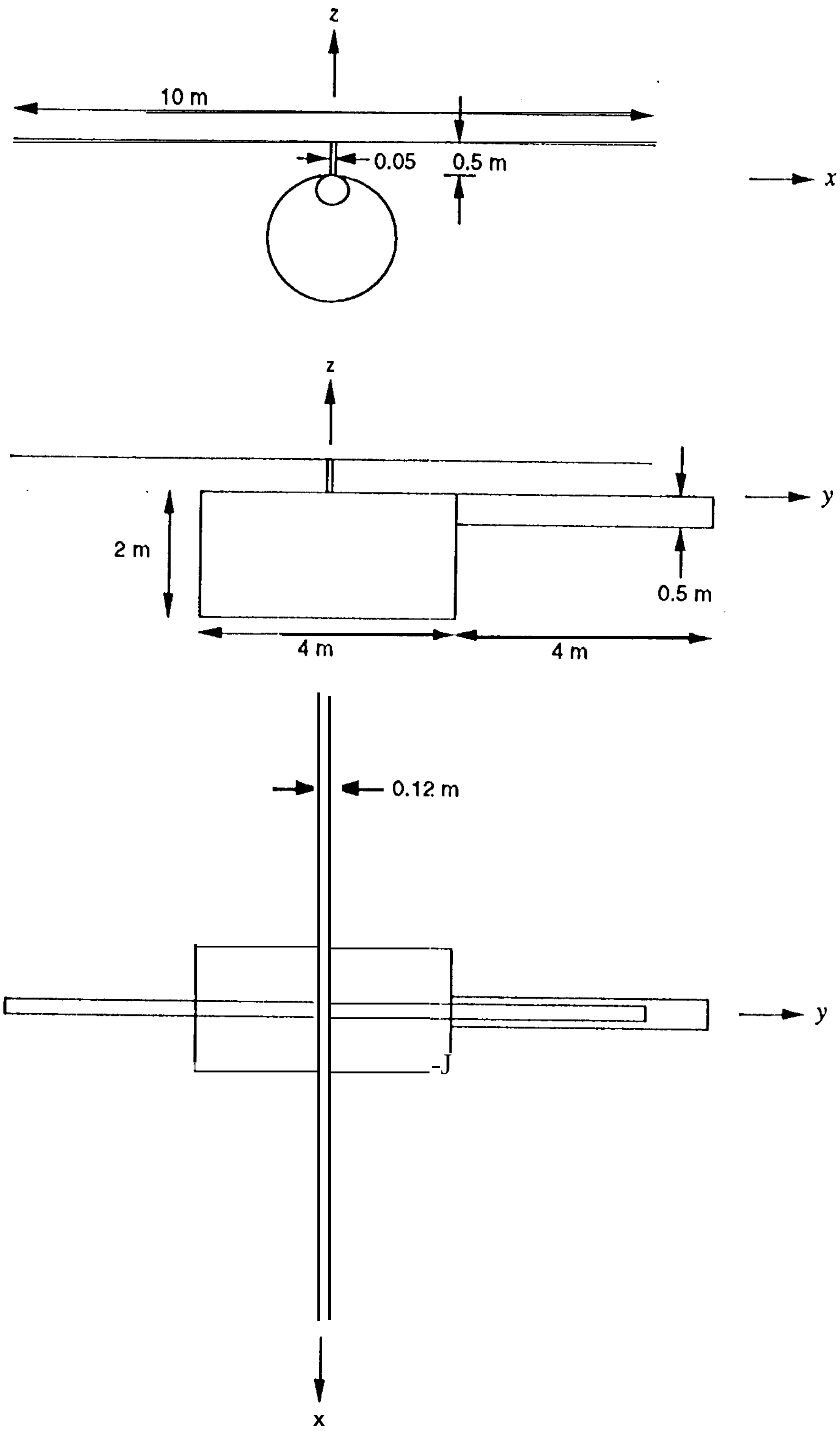


Figure b Simplified helicopter model Front view, side view, and top view.

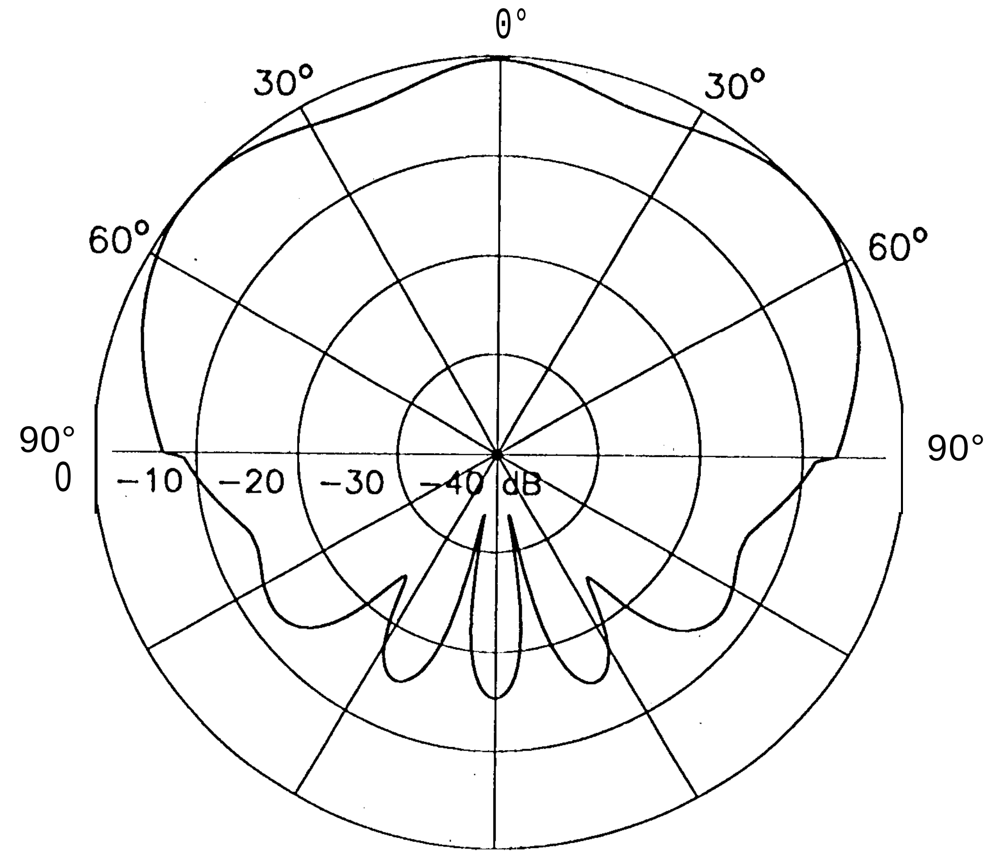
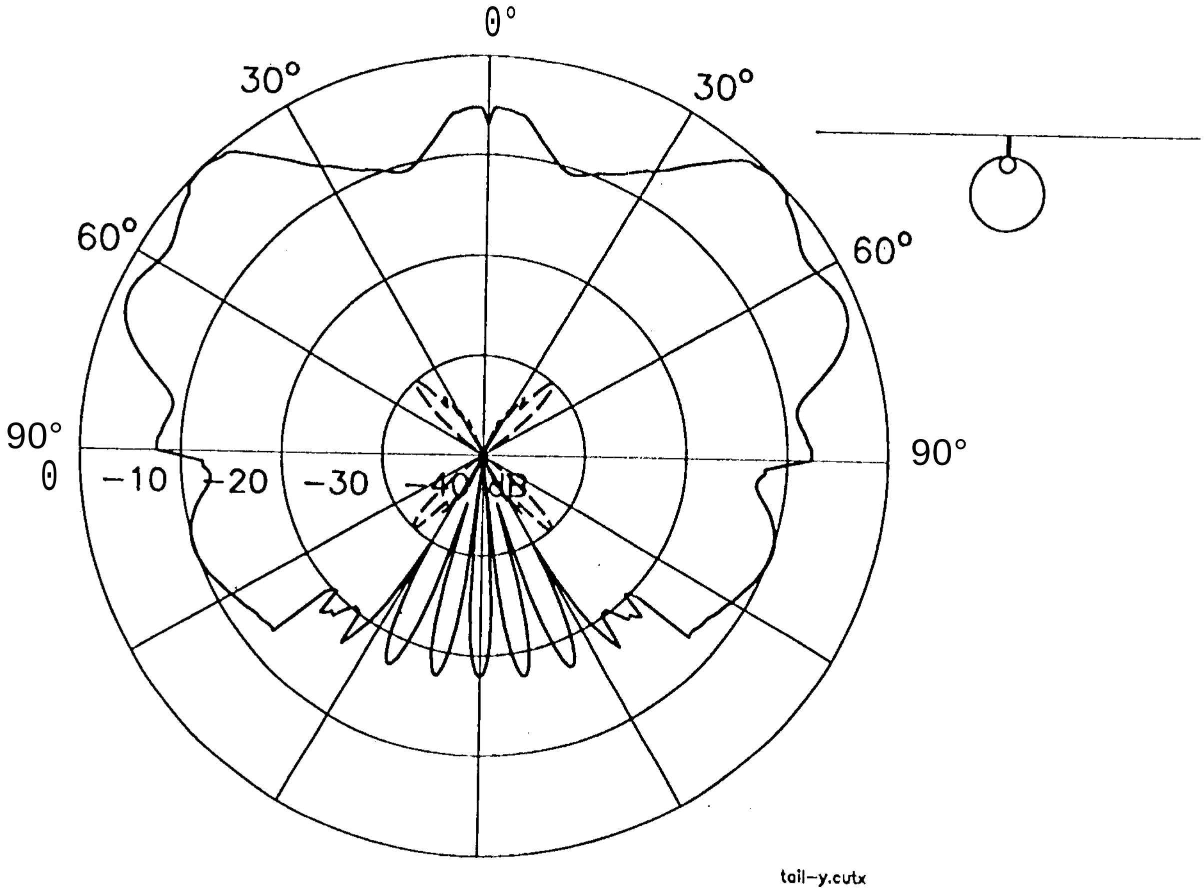


Figure 7 Radiation pattern of isolated antenna.



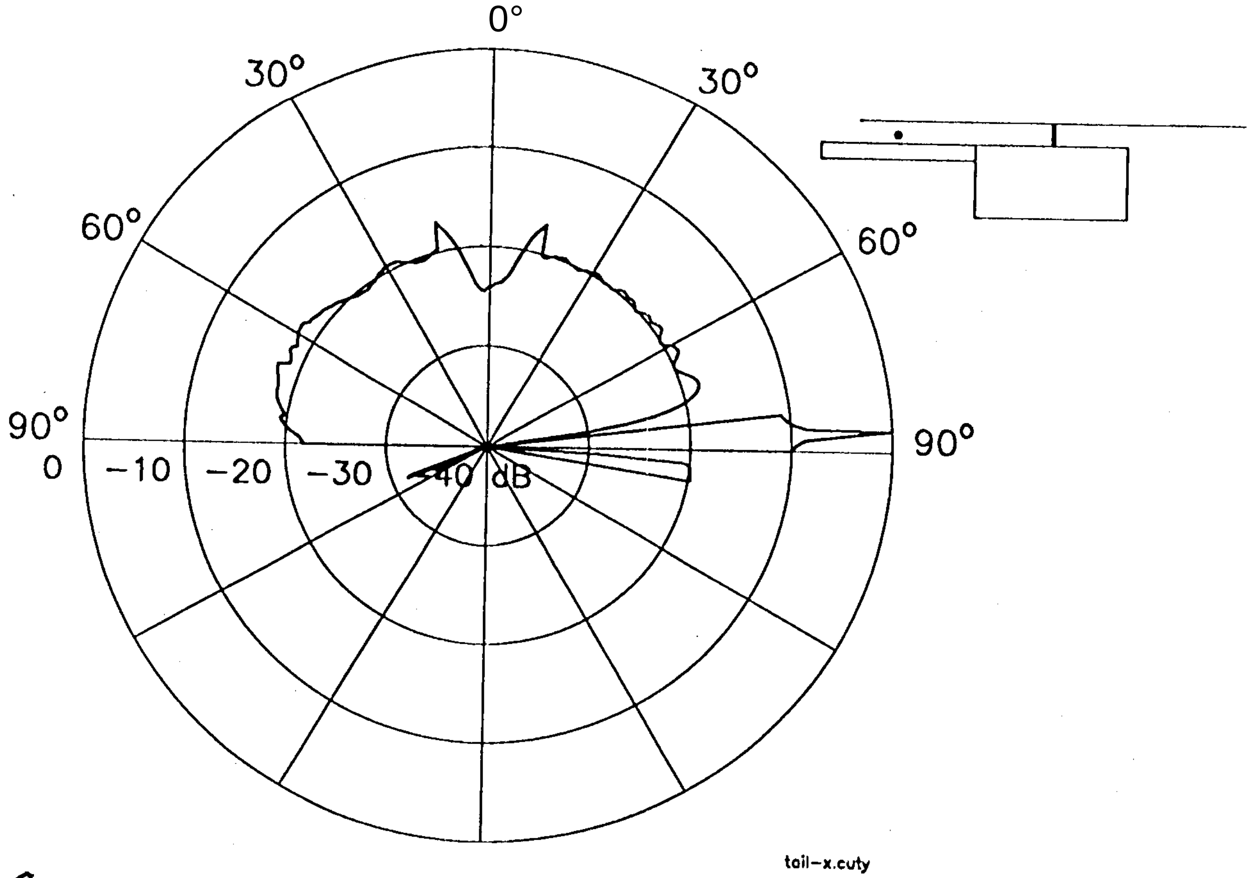


Figure 8 Radiation pattern. Antenna located on boom. Rotor blades in 0° position. (a) x-z plane. (b) y-z plane.

Biographical Sketch of Brian Abbe

B.S. Abbe received his B. S.E.E. and M. S.E.E. from Rutgers University in New Brunswick, New Jersey, in 1988 and 1990, respectively.

For the past four years, he has been working for the Jet Propulsion Laboratory (JPL), California Institute of Technology, in the area of mobile satellite communication system research and development and is currently the systems engineer for the Helicopter and General Aviation SATCOM project.

He has held several key positions during his term at JPL. His previous work included Systems/Experiments engineer on the Direct Broadcast Radio (DBSR) project, an L-band mobile satcom broadcast experiment, and Advanced Communications Technology Satellite (ACTS) Mobile Terminal (AMT) experiments manager, a Ka-Band mobile satcom project.

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Biographical Sketch of Dariush Divsalar

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His areas of interest are coding and digital modulation. During the last seven years he has taught Electrical Engineering courses and short courses at UCLA and other leading universities. He has published over 60 papers on the above and related areas and has co-authored a chapter on telemetry, systems, modulation, and coding in Deep-Space Telecommunication Systems Engineering, edited by Dr. Joseph H. Yuen (Plenum Press, 1983.) He is currently the Editor for Coding and Communication Theory for the IEEE Transactions on Communications. He is the co-recipient of the 1986 Prize Paper Award in Communications for the IEEE Transactions on Vehicular Technology. During past several years, he has been involved with the application of trellis coding to mobile satellite communications which resulted in co-authoring a book on this generic subject entitled, An Introduction to Trellis Coded Modulation with Applications (MacMillan, 1991).

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After his post-doctoral training at the University of Mississippi he has been working on the radar and satellite communication antennas in the industry. He has published 6 U.S. patents and 72 technical papers in antennas and electromagnectis.

In 1990, he joined the Spacecraft Antenna Research Group at JPL. He has worked on the ACTS mobile terminal reflector antennas, Cassini's high gain antenna, micro-spacecraft antennas and the Helicopter and General Aviation SATCOM project antenna system.

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